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# Development of New Composite Materials Based on 'Metal–Non-Metal' with Improved Functional Properties

G. E. Akhmetova, K. Tuyskhan, G. A. Ulyeva*, and E. N. Reshotkina*

*Karaganda Industrial University,*
*30 Republic Ave.,*
*101400 Temirtau, Republic of Kazakhstan*
**JSC 'ArcelorMittal Temirtau',*
*1 Republic Ave.,*
*101407 Temirtau, Republic of Kazakhstan*

The article is devoted to the possibility of using production waste with various types of binder in order to obtain new composite materials with improved functional properties. The article presents the results of experiments on obtaining new materials based on wastes of silicon and metallurgical industries—microsilica powder and zinc ash using metal (liquid tin) and non-metal (liquid glass) as binders. State diagrams during the interaction of these components, properties and microfractography of samples of fabricated materials are obtained, reviewed and analysed. The influence of binders on the strength properties of the matrix of the obtained composite materials is revealed. The resulting material of the metal–non-metal system has increased values of strength properties.

**Key words:** microsilica, zinc ash, liquid glass, liquid tin, composite material, binder, state diagram.

Стаття присвячена можливості використання відходів виробництва з різними видами зв'язувальної речовини з метою одержання нових композиційних матеріалів із покращеними функціональними властивостями. У статті наведено результати експериментів з одержання нових матеріалів на основі відходів кремнійового та металургійного виробництв — порошку мікрокремнезему та золи цинку із застосуванням як сполучних мате-

Corresponding author: Kurmetbek Tuyskhan
E-mail: k.tuyskhan@tttu.edu.kz

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ріялів металу (рідке олово) та неметалу (рідке скло). Одержано, розглянуто та проаналізовано: діяграми стану при взаємодії зазначених компонентів, властивості та мікрофрактографія зразків одержаних матеріялів. Виявлено вплив сполучних речовин на властивості міцности матриці одержаних композитних матеріялів. Одержаний матеріял системи метал–неметал має підвищені значення властивостей міцности.

**Ключові слова:** мікрокремнезем, зола цинку, рідке скло, рідке олово, композиційний матеріял, сполучна речовина, діяграма стану.

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## 1. INTRODUCTION

At present, characterized by the rapid development of the industrial industry, materials science puts before researchers the development of new materials with improved performance characteristics, provided that raw materials and energy costs are reduced. Many composites are superior to traditional materials and alloys in their mechanical and physical properties, for example, they are much lighter than metallic materials [1, 2]. This leads to a decrease in the material consumption of the entire structure while maintaining or improving its physical and mechanical characteristics. And composite materials based on metal-metal can consist of completely different in structure and properties of metals and alloys based on them. Compared to alloys of the same composition, they may have improved performance properties, including crack resistance, fracture behaviour, impact behaviour, *etc.* [3]. In accordance with this, the relevance of this work is the need to develop new technologies to produce composite materials with a unique combination of mechanical and physical properties, based on silicon production waste—microsilica—acquires an important feature [4–7].

Waste dump microsilica is a reliable, affordable and cost-effective alternative for the highly volatile and supply-sensitive primary raw material market. An important problem is the fact that during the processing of silicon, a significant amount of it turns into scrap or hard-to-recycle waste. It also requires consideration and scientific and technological development. At present, large amounts of wastes containing elemental silicon of sufficiently high purity in the form of a finely dispersed powder have accumulated, which makes the question of their utilization natural [8].

Now, the fields of application of microsilica as a hardening modifier in the production of concrete [9–12], as well as in the production of dry building mixes, concrete, foam concrete, cement, ceramics, facing slabs, paving slabs, curbs, tiles, refractory masses, rubber, coatings are known.

The authors of the presented work consider microsilica as a basis for creating new composite materials, therefore, two types of samples are

**TABLE 1.** Composition of samples.

| Components | Sample No. 1 | Sample No. 2 |
|---|---|---|
| Zinc ash, g | 5 | 5 |
| Microsilica, g | 5 | 5 |
| Binder: | | |
| liquid glass, mg | 3 | – |
| liquid tin, mg | – | 4 |

considered as starting materials: 1) based on 'metal–non-metal'—the samples consist of microsilica, zinc ash and liquid glass, 2) based on 'metal–to–metal'—the samples consist of microsilica, zinc ashes and liquid tin.

The purpose of the research is to determine the influence of the basis of the developed composite materials of the 'metal–non-metal' and 'metal–metal' systems on their strength and conductive properties.

## 2. MATERIALS AND METHODS

Microsilica powder weighing 100 g was divided into fractions of 45–63 and less than 45 μm on an analytical laboratory sieving machine 'Retsch AS200 control' [13]. The sifted microsilica powder with a fraction of less than 45 μm was thoroughly mixed with the starting materials and manually moulded in metal crucibles. The solidification time of the samples was 24 hours. Table 1 lists the formulation of the samples.

## 3. RESULTS AND DISCUSSION

Samples of the obtained new materials were tested for strength (hard-

**TABLE 2.** Results of physical and mechanical tests of the obtained samples.

| Parameter | Experiment numbers | |
|---|---|---|
| | 1 | 2 |
| The basis | Metal–Non-metal | Metal–Metal |
| Hardness, HB | 212.6 | 40.0 |
| Electrical conductivity, $\Omega^{-1}$ | is absent | is absent |
| Ultimate compressive strength, kN: | | |
| formation of cracks | 3 | 2 |
| destruction | 10 | 7.5 |

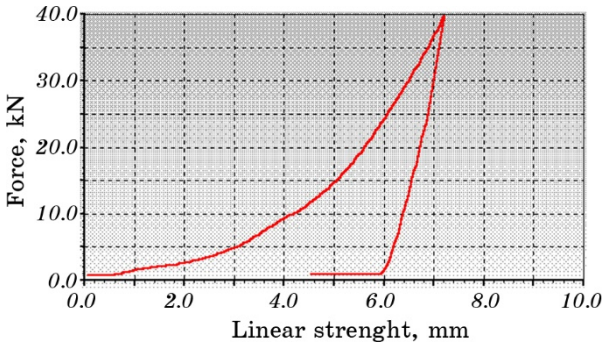



**Fig. 1.** Diagram of the compression test of sample No. 1.

ness, compressive strength) and physical (electrical resistance) properties (Table 2). The hardness was determined on the Brinell scale using a portable combined hardness tester brand MET-UD (by measuring the change in ultrasonic frequency and determining the ratio of the velocities of the striker inside the sensor before and after impact), the hardness of the obtained samples was determined. The electrical conductivity was determined by calculation, as the reciprocal of the electrical resistance measured with an ohmmeter. The compressive strength was determined using a tensile testing machine MI-40KU.

As can be seen from Table 2, the sample based on metal–non-metal has increased strength properties compared to the sample on a metal basis. This effect is associated with the influence of the binding material—liquid tin in the 'metal–metal' system, which is a ductile metal, in contrast to crystallizing liquid glass in the 'metal–non-metal' system.

Figures 1 and 2 show compression diagrams of the obtained samples.

The absence of an obvious flat area (yield area) in Figure 1 shows that the sample of the 'metal–non-metal' system is more brittle, but

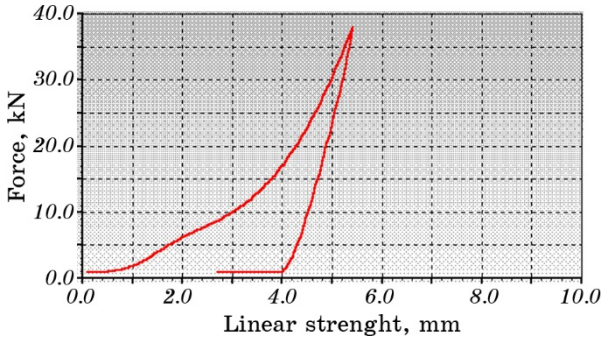


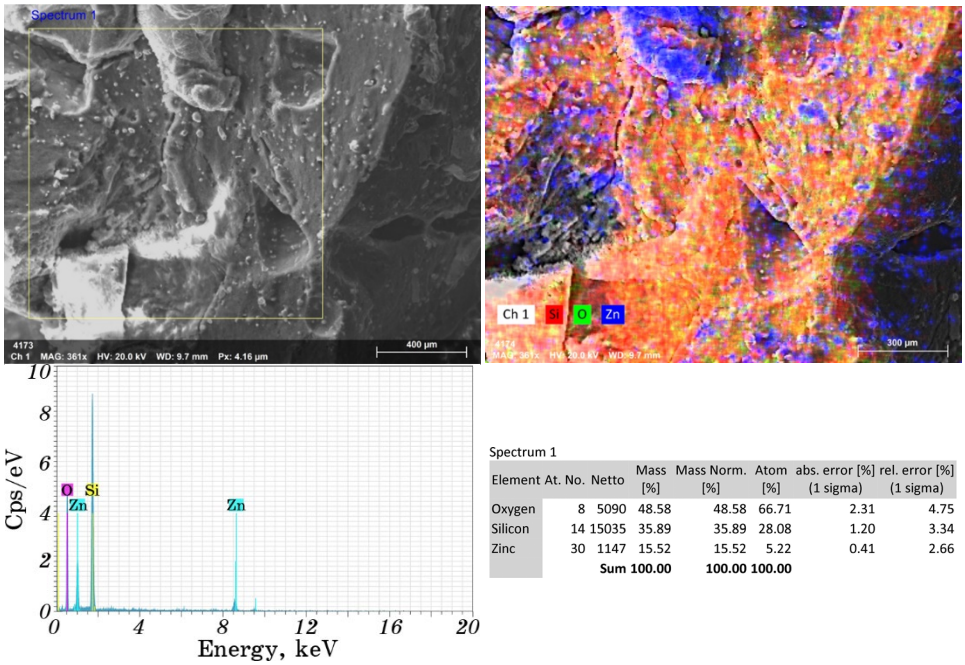

**Fig. 2.** Diagram of the compression test of sample No. 2.

stronger, in contrast to the compression diagram of the sample of the ‘metal–metal’ system, on which some yield area is traced (Fig. 2). This suggests that sample No. 2 is more ductile.

It turns out that sample No. 1, during a compression test, undergoes a stage of progressive creep that precedes failure, that is, the creep rate increases until failure. Sample No. 2 during the compression test goes through the stages of transient creep, in which the creep rate continuously decreases; the stage of steady creep, at which the creep rate is the smallest and constant; and the stage of progressive creep [14].

After the destruction of the sample, fractography was studied using a scanning electron microscope ZEIS (Germany) of JSC ‘ArcelorMittal Temirtau’ in order to determine the behaviour of microsilica with materials related in chemical composition. The choice of scanning electron microscopy is due to its high resolution and the possibility of examining the fracture surface without making replicas [15]. The use of SEM makes it possible to analyse the fractures of new materials at a higher quality level, increasing the objectivity and accuracy of fractographic studies.

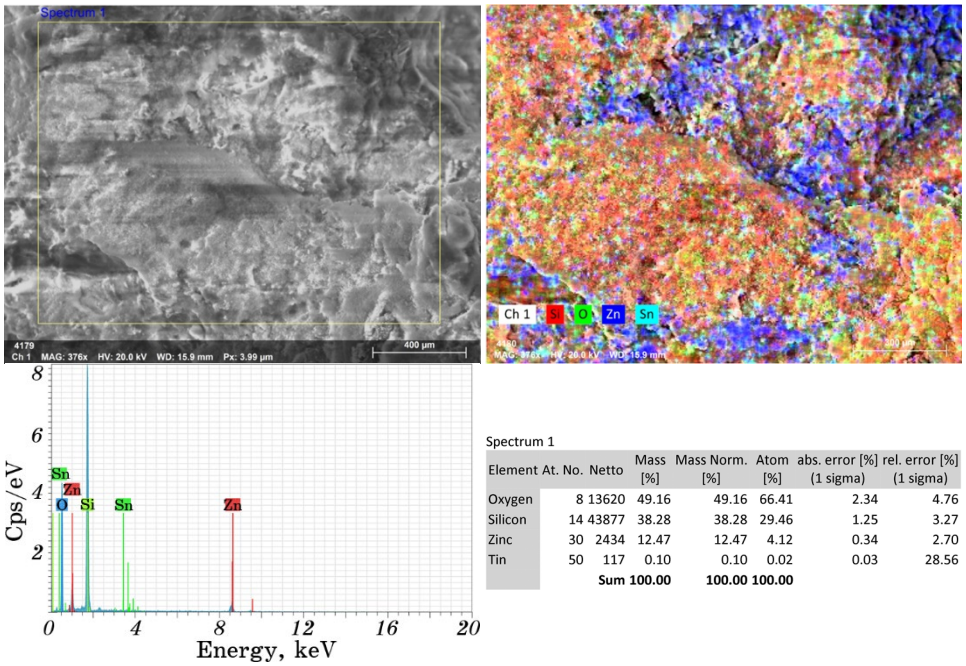
Fracture microfractography, energy dispersive analysis and the distribution of elements in the composition of the obtained samples are




Spectrum 1

| Element | At. No. | Netto | Mass [%] | Mass Norm. [%] | Atom [%] | abs. error [%] (1 sigma) | rel. error [%] (1 sigma) |
|---|---|---|---|---|---|---|---|
| Oxygen | 8 | 5090 | 48.58 | 48.58 | 66.71 | 2.31 | 4.75 |
| Silicon | 14 | 15035 | 35.89 | 35.89 | 28.08 | 1.20 | 3.34 |
| Zinc | 30 | 1147 | 15.52 | 15.52 | 5.22 | 0.41 | 2.66 |
| | | **Sum** | **100.00** | **100.00** | **100.00** | | |

**Fig. 3.** Microfractography of a fracture of a sample of the composition of microsilica–zinc ash–liquid glass (sample No. 1).




Spectrum 1

| Element | At. No. | Netto | Mass [%] | Mass Norm. [%] | Atom [%] | abs. error [%] (1 sigma) | rel. error [%] (1 sigma) |
|---|---|---|---|---|---|---|---|
| Oxygen | 8 | 13620 | 49.16 | 49.16 | 66.41 | 2.34 | 4.76 |
| Silicon | 14 | 43877 | 38.28 | 38.28 | 29.46 | 1.25 | 3.27 |
| Zinc | 30 | 2434 | 12.47 | 12.47 | 4.12 | 0.34 | 2.70 |
| Tin | 50 | 117 | 0.10 | 0.10 | 0.02 | 0.03 | 28.56 |
| | | **Sum** | **100.00** | **100.00** | **100.00** | | |

**Fig. 4.** Microfractography of a fracture of a sample of the composition of microsilica–zinc ash–liquid tin (sample No. 2).

shown in Figs. 3, 4.

Figure 3 shows that the fracture of sample No. 1 is dense, with smooth walls, and is characterized by some fibrous structure. This is due to the influence of liquid glass on the mixture of components. The use of this material as a binder causes an increase in the strength of the loose base. Also in Figure 3, there are separate areas of microsilica and fused areas of zinc burnt, along which the sample was destroyed. In this case, inclusions of zinc burnt were stress concentrators.

Figure 4 shows that the fracture of sample No. 2 is dense, somewhat embossed, there is no discontinuity, porosity. Presumably, this effect is caused by the 'healing' of pores by the binder—liquid tin, which gives increased fluidity to the composition. Due to its fluidity, it is capable of penetrating into the smallest pores and microvoids to create a reliable continuous mass [16].

In order to predict the behaviour of the initial components, the simulation of these systems was carried out with the construction of double state diagrams. The results are shown in Figs. 5–8.

Figure 5 shows that in the phase diagram of Si–Sn there is a lack of mutual solubility of the components and the implementation of eutectic crystallization at a temperature of 231.9°C, close to the melting

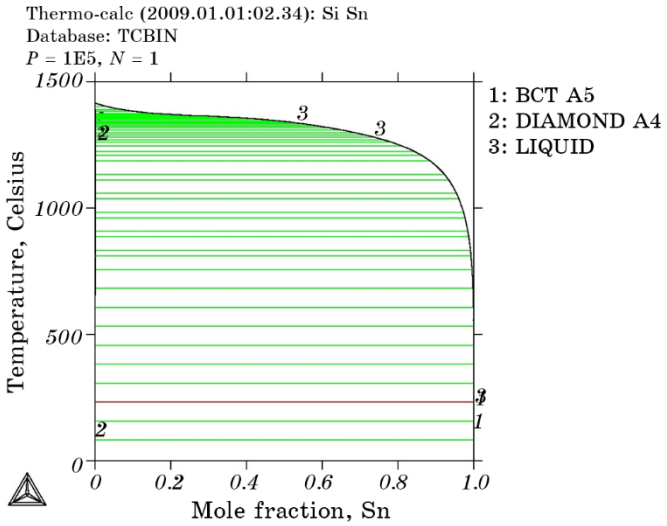



**Fig. 5.** Silicon–tin state diagram.

temperature of Sn, the eutectic is degenerate [17].

According to Figure 6, the state diagram of Si–Zn is characterized by the absence of intermediate phases and belongs to the eutectic type. The temperature of the eutectic reaction (419.58°C) is only 0.58°C lower than the melting point of Zn, and the concentration of Si in the eutectic is very low and amounts to 0.04 at.% [18].

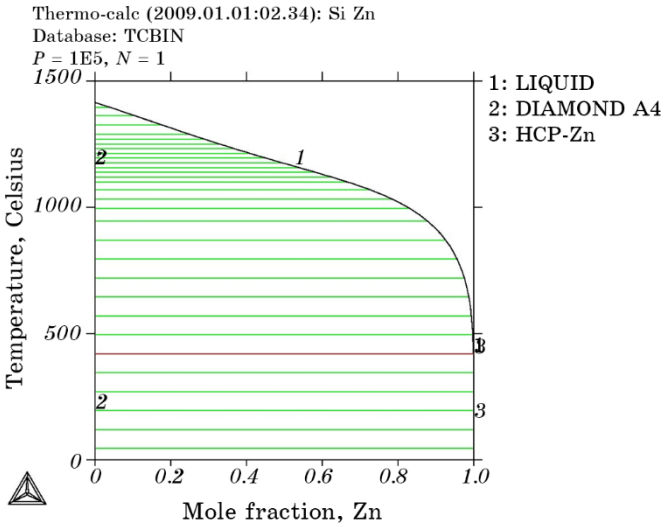



**Fig. 6.** Silicon–zinc state diagram.

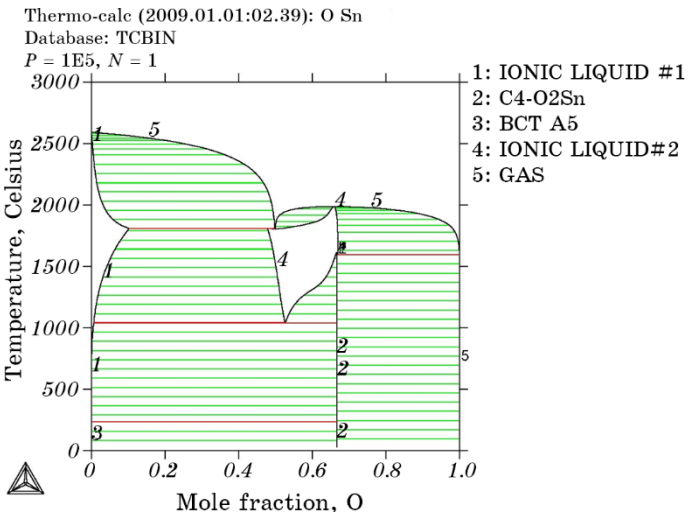



**Fig. 7.** Tin–oxygen state diagram.

That is, the state diagrams of silicon–tin and silicon–zinc are similar, and the components of the system are characterized by the absence of mutual solubility.

Figure 7 shows that the state diagram of Sn–O has phases of a solid solution, a chemical compound, a eutectoid, that is, the initial components mutually dissolve in each other in the liquid and solid state, enter into a chemical reaction and undergo a eutectoid transformation.

The state diagram of Sn–Zn (Fig. 8) is a eutectic type system without the formation of intermediate phases. The eutectic is formed at a temperature of 198.5°C and a concentration of 85.1 at.% Sn. The solubility of Sn in Zn at 400°C slightly exceeds 0.06 at.%. At the eutectic temperature, $0.06 \pm 0.1$ at.% Sn dissolves in Zn. The solubility of Sn in Zn is 0.14 at.%. At the eutectic temperature, the solubility of Zn in Sn is 0.7 at.%.

The constructed state diagrams make it possible to carry out a phase and structural analysis of the formed systems of components, their behaviour at various temperatures and concentrations, to find out the melting points of the selected compositions, *etc*.

## 4. CONCLUSION

Thus, when creating new composite materials based on microsilica ($SiO_2$), zinc ashes (ZnO), liquid tin (Sn), and liquid glass (silicate solution), it can be seen that the interaction of the components of these substances mostly contributes to the formation of a eutectic/eutectoid, and their state diagrams are of the eutectic type. This means that when

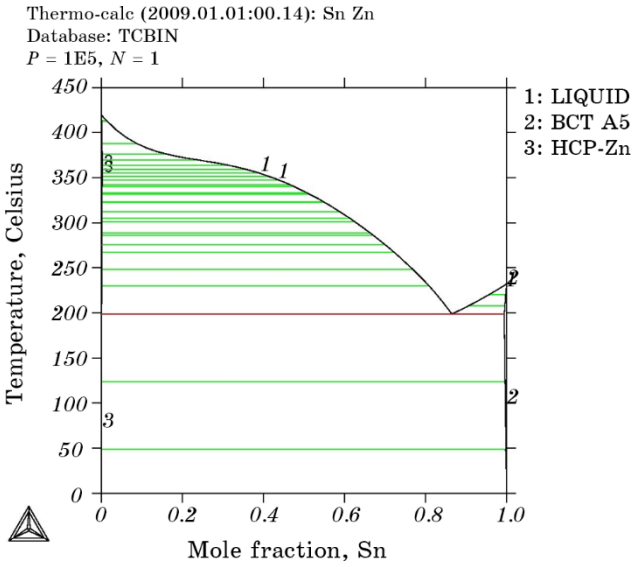



**Fig. 8.** Zinc–tin state diagram.

creating new materials, the initial components do not dissolve in each other and do not form chemical compounds (with some exceptions), and in the process of crystallization (cooling and other phenomena) they only mix, retaining the crystalline structure. Such a picture is clearly observed in Figs. 3, 4. Such eutectic (eutectoid) structures have a granular or lamellar structure. In this case, the lamellar structure can contribute to an increase in strength properties. In addition, taking into account the factor of mutual insolubility of the selected components of the systems—silicon–zinc–liquid glass and silicon–zinc–liquid tin and the melting temperatures of the binders (glass 1088°C and tin 231.9°C), we can conclude that the thermal stability of the obtained materials and their high moisture resistance.

The experiments carried out demonstrate the possibility of recycling industrial waste and obtaining new composite materials using their various combinations, which makes it possible to reduce the environmental burden of the region and expand the country's raw material base, while preserving natural resources.

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